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Exploring nitrogen indicators of farm performance among farm types across several European case studies

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ABSTRACT

Nitrogen (N) indicators are key for characterizing farm performance, because of the role of N in food production and environmental sustainability. A systematic monitoring of N balance at the farm level could contribute to understanding differences in N management and impacts among farms and among regions. The objective of this study was to increase the understanding of differences in N indicators at the farm level across Europe, and to derive possible target values.

Farm-level data were collected through surveys of 1240 farms from Atlantic, Continental and Mediterranean Europe, that were diverse rather tahn country representative. The data were analysed according to a common procedure, using three related indicators: N use efficiency (NUE, farm-gate ratio of N outputs to N inputs), N surplus and N output in agricultural products. Specific target values were derived for farm type (arable, dairy, pig and mixed farms) based on the statistical analysis of the data set. The effect of not accounting for N losses involved in the production of purchased feed and the end use of exported manure (externalisation) on the animal farm indicators was evaluated by recalculating inputs with adjusting factors.

The results show a wide variation in NUE and N surplus, mainly related to differences in farming systems and management. Arable farms presented lower mean N input and surplus than livestock farms, and therefore had the highest median NUE. The modest targets (i.e. median of data) for arable farms were NUE 61% and N surplus 68 kg N ha^{-1}, for dairy farms NUE 30% and N surplus 155 kg N ha^{-1}, and for pig farms NUE 40% and N surplus 135 kg N ha^{-1}. Externalisation had a large effect on animal farm indicators. After adjusting for externalisation, the modest target NUE for dairy farms was 19% and for pig farms 23%. Farms outside their agro-environmental optimum could approach their specific targets by increasing or reducing N inputs (intensification or extensification) or adopting additional strategies (sustainable intensification). In conclusion, N indicators were useful to compare farm performance among different farming systems and to define a characteristic operating space for a farm population, but caution should be taken when comparing livestock farms before externalisation adjustment, and consideration should be given to changes in soil N stocks. Farm system-specific targets for N indicators and linkages with the Common Agricultural Policy may create the necessary incentives to optimise NUE and reduce N losses to air and water.

1. Introduction

Nitrogen (N) is essential for life and plays a key role in food production, being among the most important crop yield-limiting factors in the world, together with water (Mueller et al., 2012). That is why most farmers apply N fertilisers, animal manures and other organic materials to the land, to improve crop yield and thus remain economically competitive (McLellan et al., 2018). However, N losses contribute to

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climate change and lead to pollution of the environment, which is harmful for the functioning of ecosystems and human health (Galloway et al., 2008; Fowler et al., 2013). Recent studies have suggested that current N losses from agriculture to the environment are too high for a 'safe operating space for humanity' (Steffen et al., 2015). Continuing population and consumption growth during the coming decades will further increase the demand for N fertiliser and may increase N losses and aggravate the trespassing of the 'safe operating space', unless significant improvements are made in the whole food production–consumption chain (Godfray et al., 2010; Sutton et al., 2013; Mogollón et al., 2018). More appropriate management of N is therefore of key importance; average crop yields and N use efficiency (NUE) will have to increase, and N losses will have to decrease (Zhang et al., 2015).

Farmers are by far the most important managers of N in terms of total N flows. There are hundreds of millions of farmers in the world, who manage a bewildering diversity of farming systems in a wide variety of socio-economic and environmental conditions (FAO, 2014). This diversity and complexity are often neglected in global scoping and assessment studies. Nitrogen is just one of many factors farmers have to consider in the decision-making process; there are no simple and standard recipes, because each region, field, crop and year has a different yield potential, N demand and N use potential. Economically competitive farmers are often well-educated and have easy access to markets, capital, technology and advice (McElwee, 2006), which results in farmers in affluent countries often having high farm incomes (Anderson, 2010). Although the EU has a history of agro-environmental regulations for N losses and obligations for monitoring N concentrations in the air and water bodies (Oenema et al., 2009), there is no common monitoring of NUE, N output and N surpluses at the farm level. There are estimations of NUE and N surpluses at the country or regional level (Liu et al., 2010; Eurostat, 2013; Lassaletta et al., 2014; Godinot et al., 2016; OECD, 2013), and there are various farm studies within a country (Nevens et al., 2005; Arregui and Quemada, 2008; Oenema et al., 2012) but few studies (e.g. Godinot et al., 2015) including farm-level case-study data from different countries that use a common format.

Nitrogen use efficiency is suggested to be a key indicator for agricultural systems (Mosier et al., 2013; Powell et al., 2010; de Klein et al., 2017), but currently neither a uniform and robust methodology and protocol nor regular monitoring suitable for international comparisons is in place. Several studies have estimated NUE in cropping, animal and whole food systems, but these studies often use different definitions, system boundaries, scales, input data and assumptions. So far, studies have been undertaken in cropping systems (Ladha et al., 2005; Dobermann, 2007; Fixen et al., 2015), and in livestock systems the emphasis has often been on dairy farms (Nevens et al., 2005; Powell et al., 2010) or in the fraction of feed N converted into meat or egg protein (Lassaletta et al., 2016). The European (EU) Nitrogen Expert Panel recently suggested using a graphical approach to present NUE, N output and N surplus in a coherent manner, as well as to indicate the difference between actual and target values suitable for international comparison of farming systems (EU Nitrogen Expert Panel, 2015).

Since there are inherent differences between different types of farms, we need to consider different agro-typologies. In this article, we focus on arable, dairy, pig and mixed farms, to develop procedures for farm comparisons. The N cycling of arable farms is relatively simple compared to that of animal farms and forms a component of the N cycling of farmas that include animal husbandry. Dairy farms are a good model to study animal farms, as the relationship between animal husbandry and grassland or cropland can follow different patterns (e.g. depending on the share of feed concentrates in the ration), they are widespread throughout Europe, and they comprise a large proportion of animal production. Mixed farms may follow different degrees of complexity and are characterised by associating animal and crop/grass production. Because of the differences in N cycling complexity among farm types, differences in the data generated from the indicators were expected to appear between arable, dairy, pig and mixed farms.

The study reported herein aimed at increasing the understanding of differences in N indicators between farm types using case study data sets from six different EU countries, so as to derive possible characteristics and target values and to identify the factors associated with differences in NUE at the farm level. In this study we applied the guidance document for assessing NUE at the farm level developed by the EUNEP (2016) based on farm data from existing data sets collected previously in countries from Atlantic, Continental and Mediterranean Europe. The data were analysed according to a common protocol and procedure, using the graphical approach of the EU Nitrogen Expert Panel (EUNEP, 2015). Finally, we investigated the influence of feed and manure externalisation on dairy farms and derived adjusting factors as an approach to compensate for varying degrees of externalisation when comparing farm NUE.

2. Materials and methods

2.1. Presentation of the data set

2.1.1. Farm sample and characterisation

Farm data were collected from six countries, situated in five of the 12 environmental zones distinguished in the EU-28: Atlantic Central (France, Ireland, The Netherlands), Atlantic North (Denmark, Germany), Continental (Germany), Mediterranean North (Spain) and Mediterranean South (Spain). The sample comprised 1240 observations from farms surveyed in the 2006–2016 period. The data originated from different studies; the farm data collected are not necessarily representative of the farms in the six countries. The common objective for all the studies was to increase the understanding of the variance in N inputs and outputs at the farm level and of the factors that contribute to this variance. A brief description of the studies is presented in Table 1.

Farms were characterised and grouped in various types according to their specialisation, measured as the output value of the main activity. According to Eurostat, farms were considered to be specialised when a particular activity (arable, dairy, pig) provided at least two-thirds of its total economic output value (Eurostat, 2013). Farms selected for the analysis were classified as arable (195), dairy (669), and pig (58) farms. Additionally, mixed dairy (182) or mixed pig farm (136) types were distinguished when crop products were sold, in addition to animal products, and the ratio of N animal outputs/total N output was < 0.75. Most farms were conventional; 11.5% were organic farms (mainly from the Danish data set, where 40% of the farms were organic, which is above the national average of 6% in the years sampled). The farm area was defined as the agricultural land in the farm and ranged from 4 to 2611 ha, with an overall mean of 120 ha.

The data set presents a large diversity of countries, environmental zones and soil conditions. This diversity is valuable for the methodological comparisons proposed in this article, but data were collected during different periods between 2006 and 2016 so they might not provide current representative data for all countries.

2.1.2. Estimation of farm-gate N balances

A unified approach was followed using the guidance document developed by the EU N Expert Panel (EUNEP, 2016). All N input and output data were collected at the farm level and reported as kg N ha^{-1} of farm area $year^{-1}$. The farm area refers to all agricultural land and includes cropland and pasture. Inputs consisted of the N entering the farm as mineral fertilisers, net feed and fodder imports, biological N fixation, atmospheric N deposition, imported N-containing soil amendments (e.g. compost and sewage sludge), seed and plant material, bedding material (straw, sawdust, etc.), net animal manure imports (see further explanation below) and N content in irrigation water. The amount of net N in imported feed and fodder was calculated from purchase data and corrected for possible changes in stock on the farm (if data were available). A tiered approach was followed for estimating N contents and specific N flows. Tier 3 was the preferred method, i.e.

Table 1
Characteristics of farm samples by farm type and country. n = number of observations.

Region	Country	n	Mean size	Soil type	Characteristics	Productivity	Description
Arable farms							
Mediterranean North	Spain	20	11 ha	Cambisols loam deep soils	Irrigated Conventional	Medium-high	Data collected on farms located in a nitrate-vulnerable zone in 2006–2007. Irrigation comes from a non-polluted river. Program to adjust N fertilisation based on soil inorganic N content. Each farm observation is the average of a 2- to 3-year crop rotation. Crop share: potato (70%) wheat (30%)
Mediterranean South	Spain	63	170 ha	Leptosol silt loam shallow soils (≈ 0.4 m)	Irrigated Conventional	Medium-high	Data collected on farms located over a nitrate-polluted aquifer in 2009–2011. Irrigation water comes either from the aquifer or a non-polluted channel. Program to adjust N fertilisation based on soil inorganic N content. Each farm observation is the average of a 2- to 3-year crop rotation. Crop share: maize (32%), wheat (18%), barley (18%), other (32%)
Atlantic North	Denmark	96	120 ha	Luvisols and podzols – sandy to clay-loams	Rain-fed (89%) Irrigated (11%) Organic (28%) Conventional (72%)	Medium-low	Data collected in the Green Accounts project (Hvid, 2010) in 2007–2008; each observation corresponds to a single farm × year. Irrigated farms are typically located on sandy soils and irrigation only used in drier years. The proportion of certified organic farms much higher than national average (6% of all farms were organic in 2007–2008).
Continental & Atlantic North	Germany	16	532 ha	Cambisols, Podzols, and Chernozems	Rain-fed Conventional	High	Data collected in the Sustainability of German Agriculture study in 2012–2014. Each farm observation is the average of a 3-year crop rotation. Crop share: winter cereals (56%), maize (10%), rape (14%) and root crops 12%).
Dairy and mixed-dairy farms							
Atlantic Central	Netherlands	285	53 ha	Podzols, sandy & clay-loam	Rain-fed Organic (1%) Conventional (99%)	High 17 800 L ha^{-1}	Data collected in the Cows & Opportunity project (Oenema et al., 2012) in 1998–2016 on 15 farms. Each observation corresponds to a single farm × year. Farms try to be ahead of average farms, in terms of productivity and efficiency.
Atlantic Central	France	74	90 ha	Cambisols, sandy to clay loam	Rain-fed Conventional	Low 5800 L ha^{-1}	Data collected in 2009–2013; each farm observation is the average over this period. Specialised dairy farms and mixed dairy and crop farms. Land share: grasslands(53%), silage maize (23%), cereals (19%). Productivity: 7716 L milk ha^{-1} forage area
Atlantic Central	France	38	108 ha	Cambisols – deep loam (> 80 cm)	Rain-fed Organic (10%) Conventional (90%)	Low 5755 L ha^{-1}	Data collected in 2012; each observation corresponds to a single farm x year. Specialised dairy farms and mixed dairy and crop farms. Land share: grasslands and alfalfa (39%), silage maize (34%), cereals (28%). High share of legumes (alfalfa, clover) in forage area. Productivity: 7200 L milk ha^{-1} forage area.
Atlantic Central	Ireland	299	66 ha	Podzols, Gleysols, and Luvisols mainly	Rain-fed Conventional	Medium-low 7200 L ha^{-1}	Data collected as part of the Teagasc National Farm Survey (Dillon et al., 2018), which provided national representative data to the EU Farm Accountancy Data Network (FADN) on a statutory basis for the Republic of Ireland in 2016. Each observation corresponds to a single farm × year.
Atlantic North	Denmark	155	175 ha	Mainly Podzols (sandy)	Rain-fed Organic (43%) Conventional (57%)	Low 6000 L ha^{-1}	Data collected in the Green Accounts project (Hvid, 2010), in 2007–2008; each observation corresponds to a single farm x year. Milk yield productivity low due to much higher proportion of organic farms than national average.
Pig and mixed-pig farms							
Atlantic North	Denmark	194	176 ha	Luvisols and Podzols, sandy to clay-loams	Rain-fed Organic (44%) Conventional (56%)	Medium	Data collected in the Green Accounts project (Hvid, 2010) in 2007–2008; each observation corresponds to a single farm × year.

the N content of agricultural commodities was based on actual chemical analysis. Tier 2 data relate to local/national validated look-up tables in publicly accessible reports, and Tier 1 data relate to look-up tables provided in the guidance document (EUNEP, 2016). Inputs of N via biological N fixation (BNF) were also derived following a tiered approach; local measurements were the preferred method when available (Tier 3). Secondly, estimations were based on equations linked to productivity of specific crops (Tier 2) and third look-up tables providing constant values per ha and crop (Tier 1). Nitrogen deposition values were derived for the individual locations from the EMEP website (EMEP, 2019) and ranged from 3 to 23 kg N ha^{-1}. The net amount of manure N imported was calculated as the difference between N imported and N exported via animal manure and furthermore corrected for possible changes in manure stock on the farm, if data were available. Hence, manure was seen as an input (and not as a harvested output) and it was only reported once, either as a positive (import − export > 0) or a negative N input (import − export < 0). Nitrogen content in irrigation water was calculated as the product of the irrigation volume times the N concentration of the irrigation water, obtained from direct measurements or from local water quality reports. The rest of the inputs were obtained directly from the farm surveys and the N contents were either measured or estimated from look-up tables (tier approach).

Nitrogen outputs were estimated from the amounts of products harvested (and leaving the farm boundary) and the mean N contents of the products, which was either measured or obtained from local validated data (Tier 3 or 2). The export of crop products was derived from yield records; crop residues such as straw were included when exported from the farm. The export of animal products was derived from selling statistics (milk, eggs, number of animals and specific weight of the animals). Only the net animal export was reported, when animals were imported and other animals were exported. Approximately 47% of the data were Tier 3, 49% Tier 2, and 4% Tier 1.

2.2. Farm N performance indicators

Once the components of the N balance were recorded, the following indicators were calculated for each farm, on area (agricultural farm area) and annual bases:

- Nitrogen use efficiency (NUE) = [Σ(N outputs) /Σ(N inputs)]. 100
- N surplus = Σ(N inputs) − Σ(N outputs)
- N output = Σ(N outputs)

Indicators were reported together for each farm: NUE as an indicator of resource efficiency, N surplus as a proxy for the N loss to the environment (assuming no changes in soil or farm stocks) and N output as an indicator of farm productivity.

2.3. Characterisation of farm performance

The characteristic operating space (COS) for each farm type was identified and target values were proposed as references to indicate the need for improving farm performance. For each farm type, NUE, N surplus and N output values were mapped onto the N input–output framework developed by the EU Nitrogen Expert Panel (EUNEP, 2015). Next, quartile regression analysis was conducted to define the 50% of farms with NUE between the first (Q1) and third (Q3) quartiles, indicated by two diagonals. The line that represented the median N surplus further identifies the COS for the farm population studied; the median N surplus was used as a possible maximum N surplus to leave out farms with higher potential N pollution losses. Finally, a horizontal boundary line was set, which was derived from the first quartile of N output and thus was exceeded by 75% of the farms (Q1) for each farm type. This minimal productivity was included to emphasise the need for producing sufficient food protein.

The median (Q2) NUE was proposed as a modest target and the Q3 NUE value as an ambitious target. Similarly, the median N surplus was proposed as a modest target and the Q1 as the ambitious target. However, it is important to note that N surplus targets should also be adapted to local or regional environmental limitations. The Q1 N output was considered as a minimum, the median as a modest target and the Q3 N output as an ambitious target, for each farm type. In practice, N output will also strongly depend on crop rotation and environmental conditions (soil, climate), and hence targets for N output will have to be set for different farm types, crop rotations and at regional levels. Here we review differences among farm types; differences among specific crop rotations were not analyzed.

2.4. Externalisation of feed production and manure export

Externalisation in this context means N losses that are directly related to the farm under investigation but not accounted for because they occur outside the farm area, e.g. during production of purchased feed or during use of exported manure. To evaluate the effects of externalisation on NUE, N surplus and N output of livestock farms (and mixed crop/livestock farms), the adjusted N input was estimated in three different ways. In the first case, N input_1 was calculated by multiplying the net imported feed N by a factor of 2, implying that the imported feed was produced with a NUE of 50%. In the second case, N input_2 did not include manure N export as a negative input, implying that the exported manure N was not used efficiently (for instance when denitrified in manure treatment plants or applied at rates above crop demand). In the third case, N input_3 was calculated as a combination of cases N input_1 and N input_2.

Next, a sensitivity analysis was conducted to evaluate the effects of changes in the estimated NUE of imported animal feed. For N input_1, calculations were made for NUE values of 25%, 50% or 75% for the imported feed produced outside of the farm. A NUE of 25% for feed production is representative of low-efficiency crops (Mosier et al., 2004; Fageria and Baligar, 2005), whereas a NUE of 75% represents highly efficient feed production systems (e.g. forages) and/or the utilisation of by-products of the food industry for concentrate production (Whitehead, 2000; Fageria and Baligar, 2005). For the manure exported, sensitivity analysis of N input_2 included varying NUE values for the manure exported ranging from 0% (manure was not regarded as effective at all, i.e. considered a waste product) to 20% (for low N-efficiency manure use) to 70% (for manure applied to cropland via low-emission techniques). A NUE of 20% for manure N has been reported in low-efficiency farms in which manure is applied directly to grasslands (Beegle et al., 2008; Webb and Erasmus, 2013), whereas a NUE of 70% has been reported for cattle and pig slurries applied with low-emission techniques, e.g. via injection into the soil or following acidification of the slurry (Webb and Erasmus, 2013).

2.5. Data analysis

Statistical analyses were performed with R language (R Core team, 2018). The analyses consisted of descriptive statistics of the NUE, N surplus, N output and N input results by farm typology, analysis of variance using the general linear model procedure, comparisons of means by the post-hoc Tukey test ($p < 0.05$), simple regression analysis and sensitivity analysis to estimate the influence of N inputs on N indicators as previously described.

3. Results and discussion

3.1. Farm indicators in the data set

Analysis of variance showed a significant effect of farm specialisation on the farm N indicators studied ($p < 0.001$). The pairwise comparison of means distinguished five different NUE groups in the

Table 2
Farm N indicator statistics for various farm types before and after adjusting for externalisation of feed and manure. Q1 and Q3 are the first and third quantiles of the probability distribution of data sets in each farm type. *n*, number of observations; id, identical values for n and N outputs.

Farm types	n	N input (kg N ha^{-1})				N output (kg N ha^{-1})				N surplus (kg N ha^{-1})				NUE (%)			
		Mean	Median	Q1	Q3	Mean	Median	Q1	Q3	Mean	Median	Q1	Q3	Mean	Median	Q1	Q3
Before adjusting for N externalisation																	
Arable	195	176a	174	146	199	105b	100	75	127	72a	68	42	97	60e	61	45	75
Mixed dairy	182	205b	197	168	233	81a	73	57	92	124b	120	101	147	39b	38	32	44
Dairy	669	245c	236	179	300	74a	64	43	98	170c	156	126	212	30a	28	21	38
Mixed pig	136	278d	266	225	325	153c	143	112	181	126b	122	98	149	54d	55	47	61
Pig	58	253d	250	220	279	114b	103	89	127	139b	138	116	161	44c	43	37	51
After adjusting for N externalisation*																	
Mixed dairy	id.	301b	267	198	361	id.	id.	id.	id.	221b	195	141	273	28b	26	23	31
Dairy	id.	378c	322	230	459	id.	id.	id.	id.	303c	255	183	372	20a	19	17	22
Mixed pig	id.	516d	473	359	638	id.	id.	id.	id.	363d	322	235	464	31d	31	26	35
Pig	id.	488d	450	383	534	id.	id.	id.	id.	375d	345	289	408	24c	23	21	26

Within before or after adjusting for N externalisation, means followed by different letters in the same column are significantly different at $p < 0.05$.
* Adjusting for N externalization consisted in calculating N inputs by multiplying the net N imported as feed by 2 (corresponding to a NUE of feed production of 50%) and not considering manure N output as a negative input (assuming zero N fertiliser value for manure).

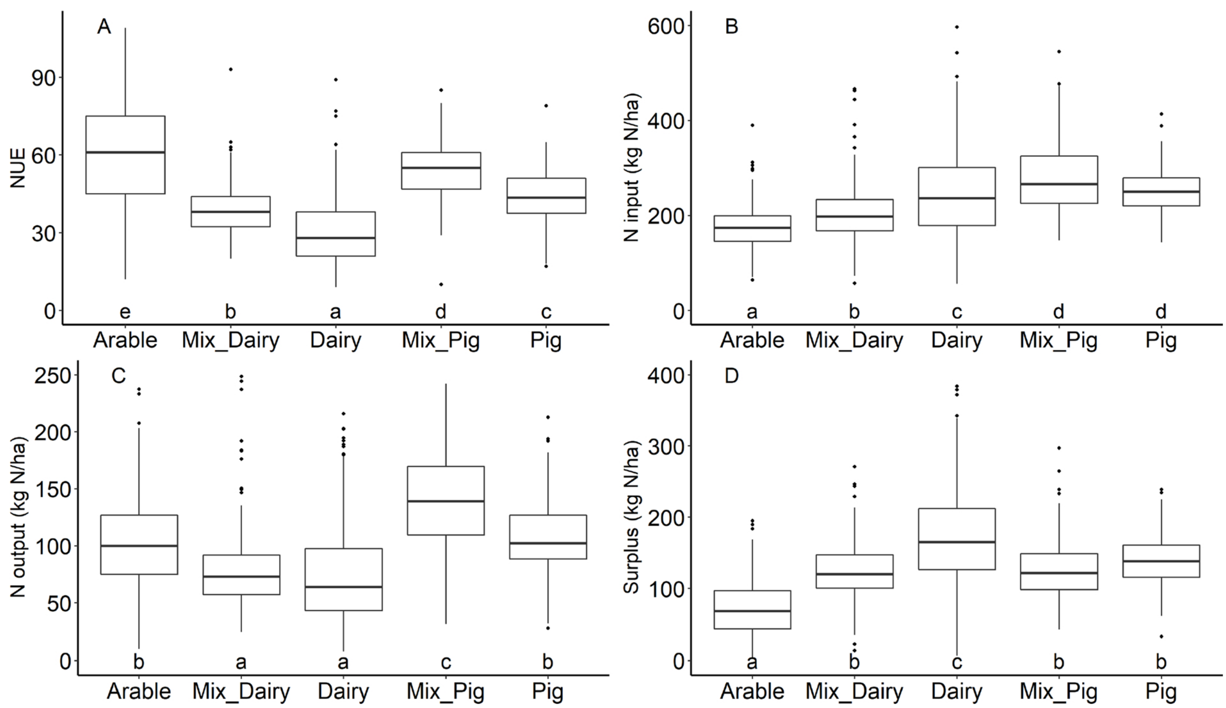

Fig. 1. Boxplots of indicators for various farm types: (A) nitrogen use efficiency (NUE), (B) nitrogen input (N input), (C) nitrogen output (N output) and (D) nitrogen surplus (Surplus). Boxes and whiskers show 5 and 95% percentiles, boxes 25% (Q1) and 75% (Q3) quartiles and the line in the middle the median; single dots indicate outlying values. The sample size was 195 arable farms, 182 mixed dairy, 669 dairy, 136 mixed pigs, and 58 pig farms.

data set (Table 2; Fig. 1A). Mean NUE was the largest for arable farms (60%) and lowest for dairy (30%), with pig farms between the two. Mixed farms had NUE values between arable and animal farms, with a mean NUE of 39% for mixed dairy farms and of 54% for mixed pig farms. These results agree with literature data and highlight the inherent greater N efficiency of crop versus animal production. Reported NUE values for arable farms in Europe are in the range of 60–65% (Schröder et al., 2003). The NUE of sole crop production in grassland-based dairy farms ranged from 56 to 91% (Oenema et al., 2012), while NUE of whole dairy farms ranged from 15 to 40% in the US, Australia, The Netherlands and New Zealand (Powell et al., 2010; Gourley et al., 2012; Oenema et al., 2012; de Klein et al., 2017). Potential NUE values for pig farms ranged between 41 (Cederberg and Flysjö, 2004) and 49% (Godinot et al., 2015) and tended to increase in mixed farms when both crops and pigs are exported (Willems et al., 2016).

Pairwise comparison of N inputs means by farm type distinguished four groups (Fig. 1B). Mean N inputs were the lowest for arable farms (178 kg N ha^{-1}) and highest for pig and mixed pig farms (266 kg N ha^{-1}). Dairy farms constituted a different group and mixed dairy farms were between arable and dairy. Comparison of N outputs distinguished three groups only (Fig. 1C). Mean N outputs were the lowest for dairy and mixed dairy farms (77 kg N ha^{-1}), followed by arable and pig farms, and were the largest for mixed pig farms (153 kg N ha^{-1}). Mixed dairy farms exported much less N as animal products than dairy farms, but compensated by exporting crop products (Table 3). More N was exported via animals from pig farms than from mixed pig farms. However, pig farms exported much less N via harvested crops than mixed pig farms (Table 3). On dairy and arable farms in particular, N outputs in general were highly variable, reflecting differences in cropping systems and/or environmental conditions (Table 1).

Mean N surplus was lowest for arable farms (mean, 72 kg N ha^{-1}) and highest for dairy farms (mean, 170 kg N ha^{-1}; Table 1, Fig. 1D).

Table 3
Net nitrogen exported in the form of crops or animals (including animal products and animals) for the various specialised farms. Values expressed as mean (standard error).

Specialisation	Crop products (kg N ha^{-1})	Animal products (kg N ha^{-1})
Arable	106 (46) a	0 (1) a
Mixed dairy	37 (26) c	43 (22) b
Dairy	2 (4) a	73 (40) c
Mixed pig	71 (28) d	82 (46) d
Pig	16 (10)b	98 (38) e

Means followed by different letters are significantly different at $p < 0.05$.

The other farms constituted a single group with a mean N surplus of 130 kg N ha^{-1}. High N surpluses of 110–320 kg N ha^{-1} were previously reported for dairy farms (Powell et al., 2010; Gourley et al., 2012; Oenema et al., 2012; de Klein et al., 2017) and reflect high potential environmental risks associated with N losses to air and water.

Analysis of variance showed a significant effect of farm typology on farm characteristics associated with N indicators ($p < 0.001$). Mean farm area was the largest for arable farms (209 ha) and lowest for dairy farms (66 ha), with pig farms (194 ha) between the two (Fig. 2A). Mixed dairy farms had on average twice the area compared to dairy farms. Evidently, our data set included both low- and high-intensive dairy production systems, which are related in part to differences in farm structure among countries (Table 1). Differences in mean farm area between pig and mixed pig farms were relatively small; the data of all pig and mixed pig farms came from Denmark where environmental policies oblige pig farms to have sufficient farm cropping area available for manure application and where pigs are largely fed with crops produced on the farm (Willems et al., 2016). No significant difference in animal density was observed between pig and mixed farms (Fig. 2B), whereas dairy farms had the highest mean animal density (2.3 LU ha^{-1}).

3.2. Arable farms

Quartile regression analysis indicated that 50% of the arable farms had NUE values within the range of 45–75% (Fig. 3A, Table 2). The median N surplus was 68 kg N ha^{-1}. In terms of productivity, 75% of the farms had N outputs exceeding 75 kg N ha^{-1} (Q1).

Some arable farms in Germany and Spain achieved approximately 80% NUE. The EU Nitrogen Expert Panel (EUNEP, 2015) has suggested a maximum threshold at 90% NUE to identify where there may be a risk of mining soil N (and organic matter) and thus induce soil N depletion and degradation of soil fertility and soil carbon. This data set did not have long-term series to analyse the risk of soil degradation. However; for single crops in a 3-year rotation in Spain, NUE sometimes turned out to be higher than 100%, especially when soil available N before sowing a crop was high. These data came from a programme designed to convince farmers to adjust fertiliser application by soil available N in order to decrease potential N losses. Evidently, mining soil nutrients for a certain period can be a good practice when soil fertility levels are high and may temporally lead to very high NUE values. This may occur when crops with high N uptake capacity (i.e. winter cereals) follow crops that leave high residual N in crop residues and/or the soil after harvesting (i.e. poppy, garlic, tomato); hence these subsequent crops scavenge N from the previous crop. Defining the COS for farms producing different mix of crops may be complex as the capacity of uptake and export N may be specific to a crop, but the actual NUE and N output is affected by the crop context in the rotation. Farm-level NUE will average the different crops of a crop rotation and is therefore a better estimate of the actual overall NUE in practice than NUE of individual crops. Data from long-term series, including at least a whole crop rotation, are recommended, to average out such annual variations.

Another factor influencing NUE in arable farms was manure application. For example, Danish arable farms in the data set had relatively low NUE and high N surpluses (Fig. 3A), likely due to a higher use of animal manure than the others (mean 58 kg N ha^{-1}, versus 23 in Germany and none in Spain). The Danish arable farms in the data set were also characterised by a high proportion of organic farms (28%), which do not use mineral N fertilisers at all, and only rely on imported manure and N-fixing crops or green manures for N supply, but also conventional Danish arable farmers import manure from neighbouring livestock farms. Case et al. (2017) found that 72% of all Danish farms use organic fertilisers (manures, sludge or composts). High estimated N surpluses in organic farms and conventional farms where manure is applied could be partially explained by the storage of N in soil organic matter, as soil organic carbon typically increases in these systems (Maillard and Angers, 2014; Gattinger et al., 2012), which would imply that a share of the estimated surplus is not actually a loss to the environment but a contribution to C sequestration and fertility buildup. There are various practices to minimise N losses from organic fertilizers applications but attaining high manure N recovery at a farm level is more difficult with manure than with mineral fertilisers (Lasa et al., 1997; Quemada et al., 1998; Beegle et al., 2008; Webb and Erasmus, 2013). Denmark was the only country with both arable and animal farms in the data set, showing how manure export may increase the NUE of animal farms while leading to relatively lower NUE values of those arable farms utilising the manure. The manure transport and distribution improves overall N cycling and promotes better utilisation by linking animal farms to crop farms; this emphasises the importance of establishing and evaluating N balances not only at the farm level, but also at regional and national levels.

The modest target NUE for arable farms was 61%, and the ambitious target 75% (Table 2). The target N surplus was set at the median (68 kg N ha^{-1}) and the ambitious one at 42 kg N ha^{-1}. In terms of productivity, the N output varied from 60 kg N ha^{-1} in some Danish and Spanish farms to > 200 kg N ha^{-1} for some German farms. This

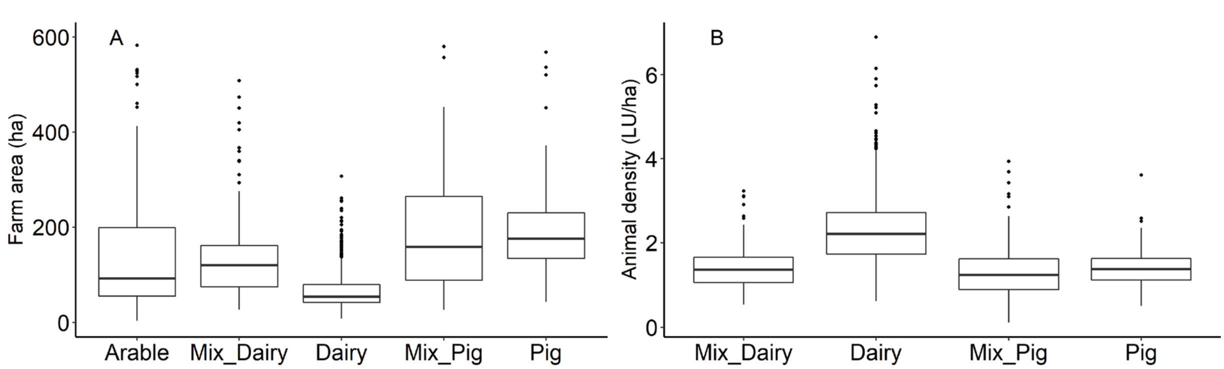

Fig. 2. Farm characteristics for the various specialisation farms: (A) farm area and (B) animal density. Boxes and whiskers show 5 and 95% percentiles, boxes 25% (Q1) and 75% (Q3) quartiles and the line in middle the median; single dots indicate outlying values.

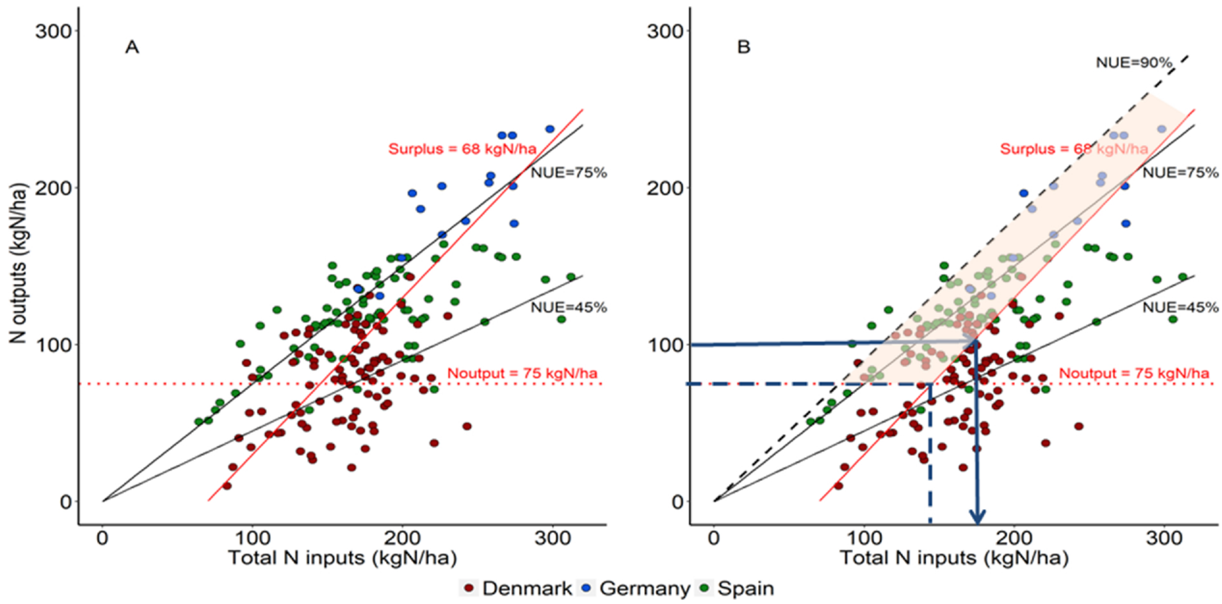

Fig. 3. Farm indicator values (A) and (B) application of the characteristic operating space (shaded area) to the arable farms in the data set. Symbols with different colours represent farm observations from different countries. For further details, see text.

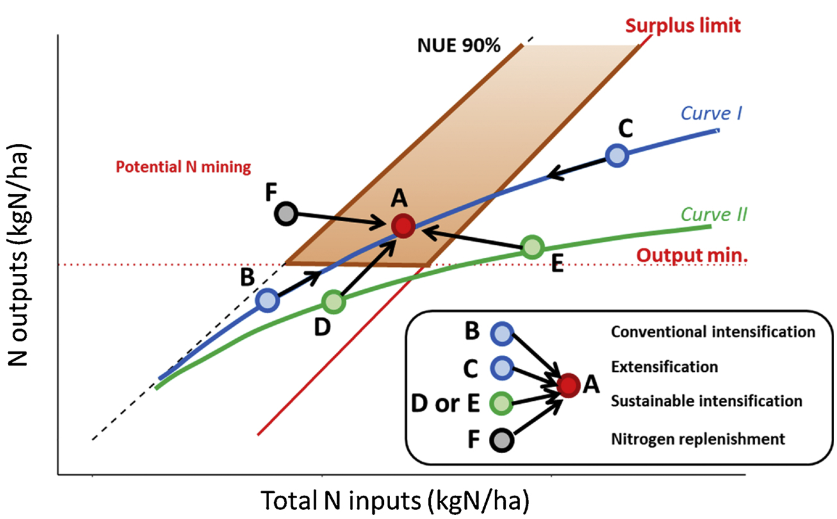

Fig. 4. Ideal pathways that any farm could follow to enter the characteristic operating space (A, shaded area). Farms whose yield–N input relationship fits Curve I with high potential maximum yield (B and C), could reach the operating space by increasing (B) or decreasing (C) fertilisation rates (conventional intensification and extensification, respectively). Farms with poorer yield/N input relationships (Curve II) should also act on factors other than N inputs to improve the general performance of the system, a sustainable intensification pathway (D and E). Farms mining soil nitrogen (F) have to replenish N outputs by adjusting the inputs.

variability is related to differences in crop rotations and environmental conditions (Table 1).

3.2.1. Transition pathways

So how can the farm data depicted in the N input-output framework in Fig. 3 be used by the individual farmer? A farmer with low productivity (N output $<$ Q1) could decide to strive to improve his or her farm. Based on the arable data set here, a farmer could target a productivity equal to the median N output (Q2 = 100 kg N ha^{-1}) or at least greater than Q1 (dashed horizontal line in Fig. 3B). However, this N output should be achieved within a maximum N surplus target to avoid environmental pollution, as indicated by the red line (here the median N surplus = 68 kg N ha^{-1}). Furthermore, a minimum NUE target corresponding to Q1 in the data set (45% for the arable data set) and a maximum target NUE = 90% to avoid soil mining (dashed diagonal line in Fig. 3B) will further delimit a COS, within which most farms are expected to be. Depending on the specific conditions (climate, market prices, newly acquired technology, policy, etc.), the farmer will be able to choose more modest or more ambitious targets. It is worth noting that the N output target is defined by the farmer (usually based on farm characteristics, productivity or profitability criteria), the NUE targets by the data set (farm typology, region, etc.) and the N surplus (or the N input) by environmental sensitivity and policy.

An additional application of this COS concept analyses the effect of environmental policy implementation. If new rules are implemented in a region to limit farm N losses by capping either the N surplus or the N inputs (e.g. European Nitrates Directive regulating fertiliser inputs or the new German fertiliser ordinance), the impact on the farm population can be estimated by plotting the new regulatory limits. Usually, new N surplus targets would be between the median and the Q1 of the data set, and by plotting the new diagonal a new COS will be defined. A safe operating space could be defined in the N input-output framework, and policies implemented to facilitate farms and the COS moving toward this safe space. Highly productive farms (N output $>$ Q3) that are operating in the safe operating space could be used as models for farm performance, against which the farm management practices of more poorly performing farms could be benchmarked.

Once the COS is defined as safe for a specific farm typology system and region, any farmer could check if his/her farm's performance falls within this space. If not, the question is what to do to move the farm inside of the COS. The first step is to know where in the panel the farm is located. Fig. 4 illustrates several contrasting options in a general theoretical framework where A represents the target to be reached inside the COS quadrangle. We first assume that the yield-N input relationship fits a classical curve of diminishing returns (de Wit, 1992; Lassaletta et al., 2014). This means that under constant agronomical and technical conditions, other limiting factors will impose an upper yield limit at saturating N availability. In Fig. 4 two yield-N input response curves (I and II) are represented. Curve I has a higher maximum yield value, or Ymax (yield value reached at saturating N input), than Curve II and therefore its agro-environmental performance is better. Farm B (Fig. 4) could reach the COS simply by increasing N inputs following a traditional intensification pathway. Farm C on the other hand, would have to approach the COS by decreasing N inputs, that is, by means of an extensification pathway. Farms D and E cannot reach the COS only by changing N fertilisation rates, since they are on the lower response Curve II, and changing N inputs will not bring their performance within the COS. Instead, they need to undertake other management strategies resulting in an increase of agro-environmental performance through a transition towards a new yield-N input response curve (Bodirsky and Müller, 2014). This transition can be considered as a sustainable intensification pathway. Farm D needs to invest in improving performance together with increasing N inputs, while farm E instead requires both improved response and a reduction of N inputs. Farm F extracts higher N than that provided in the inputs with the potential to mine soil N, diminishing soil fertility and potentially compromising long-term sustainability. Extracted N has to be replenished to avoid further degradation.

3.3. Livestock farms

The Q1 and Q3 NUE values for specialised dairy farms ranged from 21 to 38% and the median N surplus was 156 kg N ha^{-1} (Table 2; Fig. 5A). In terms of productivity, 75% of the farms had N outputs exceeding 43 kg N ha^{-1}.

The modest target NUE for dairy farms was set at 28%, and the ambitious one at 38%. The median N surplus was 156 and the Q1 was 126 kg N ha^{-1}. NUE values higher than 50% in dairy farms are likely to be associated with externalisation of feed production and potentially soil N mining, as discussed further below. Very high NUE values for livestock farms can only be obtained through a combination of a high NUE at the herd level and at the soil/crop level, and requires that the manure N is effectively utilised (Gourley et al., 2012; Oenema et al., 2012). This suggests that there is an upper threshold for NUE of livestock farms, but our data are not sufficient to derive this value. Therefore, we chose to keep the 90% NUE upper boundary for all farm types, although this limit is not likely to be attained in livestock farming systems.

A common intensification practice, which results in enhancing NUE of dairy farms, is externalising feed production and manure export (de Klein et al., 2017). Feed is imported for cows as concentrates (and sometimes forages), so N losses associated with the production of the imported feed are not accounted for in common N balances and NUE calculations. In a similar way, when manure is exported from the farm, e.g. due to lack of arable or forage land where it can be applied, N losses associated with the application and utilisation of this manure are externalised and not accounted for. Our data set contained dairy farms from four different countries, and it is clear that there were structural differences between these farms (Table 1); therefore, we analysed the effects of externalisation on farm N indicators.

Dairy farms from the Netherlands had high productivity (mean, 17 800 L milk ha^{-1}) and animal density (2.9 LU ha^{-1}), but also high externalisation by both feed import and manure export (Fig. 6). Danish farms had lower productivity (mean, 6000 L milk ha^{-1}) and animal density (1.5 LU ha^{-1}), and medium externalisation by importing feed and exporting manure. French and Irish dairy farms relied mainly on grassland grazing and forage produced on the farm, and had low feed import and no manure export (Fig. 6). French farms had low productivity (mean, 5786 L milk ha^{-1}) and animal density (1.2 LU ha^{-1}), whereas Irish farms had slightly higher productivity (mean, 7200 L milk ha^{-1}) and animal density (2 LU ha^{-1}). No differences were found in milk quality (i.e. N content per L of milk) between countries for

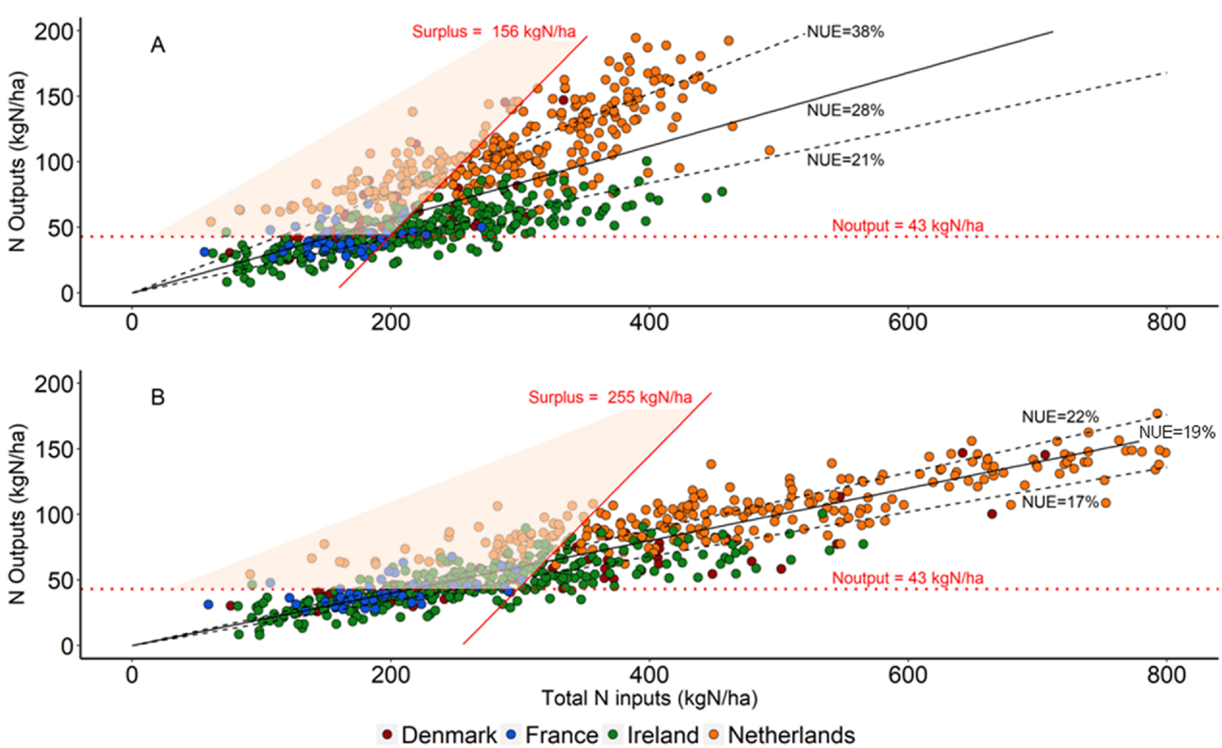

Fig. 5. Farm indicator values and application of the characteristic operating space (shaded area) to dairy farms in the data set (A) before adjusting N inputs for externalisation and (B) after adjusting N inputs for externalisation. Symbols with different colours represent farm observations from different countries. For further details, see text.

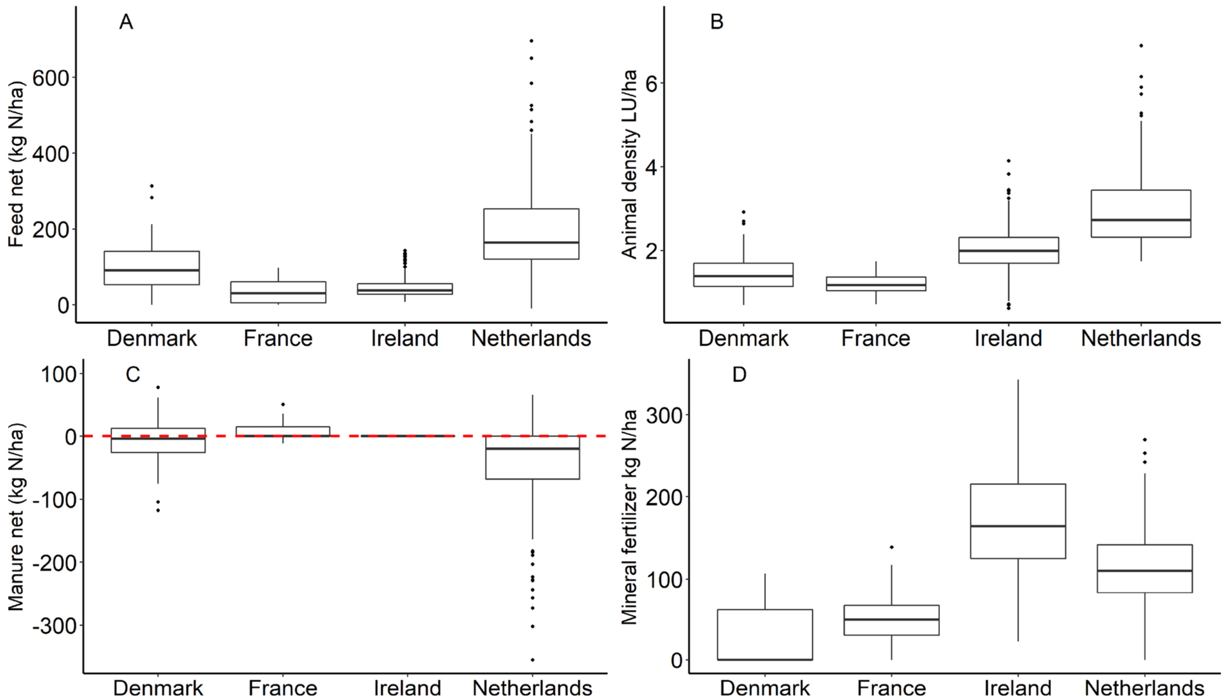

Fig. 6. Boxplots of (A) net N imported as feed, (B) animal density, (C) net N manure imported and (D) N applied as synthetic fertiliser on the dairy farms in the data set from the different countries. Boxes and whiskers show 5 and 95% percentiles, boxes 25% (Q1) and 75% (Q3) quartiles and the line in the middle the median; single dots indicate outlying values.

which data were available (France, Ireland, The Netherlands).

Analysis of variance showed a significant difference between countries in farm N indicators ($p < 0.001$). The pairwise comparison of means distinguished four different NUE groups in the data set (Fig. 7A). The highest mean NUE was attained by Dutch farms; these farms also had the largest N inputs and N surpluses (Fig. 7B, C). The lowest mean NUE were Irish dairy farms; these had relatively high N inputs and N surpluses. The N inputs were mainly in the form of mineral N fertiliser, for increasing grassland productivity (Fig. 6D). Dutch farms exported manure and imported much more feed than the dairy farms in the other countries (Fig. 6A, C). The high productivity and NUE of Dutch dairy farms is partly related to the externalisation of feed production and the export of manure. Danish and French farms had low N surpluses, which was related to more limited N inputs (Fig. 7B, D).

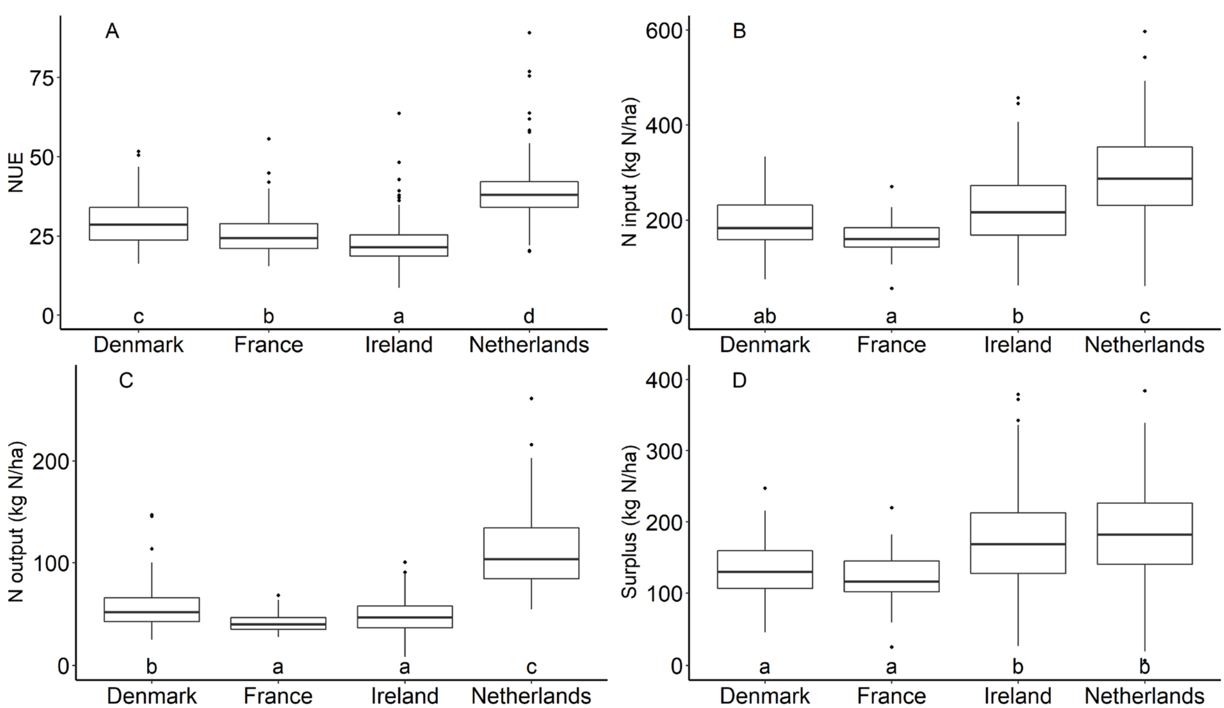

Fig. 7. Boxplots of the indicators for dairy farms in the data set from the various countries: (A) nitrogen use efficiency (NUE), (B) nitrogen input (N input), (C) nitrogen output (N output) and (D) nitrogen surplus (Surplus). Boxes and whiskers show 5 and 95% percentiles, boxes 25% (Q1) and 75% (Q3) quartiles and the line in the middle the median; single dots indicate outlying values.

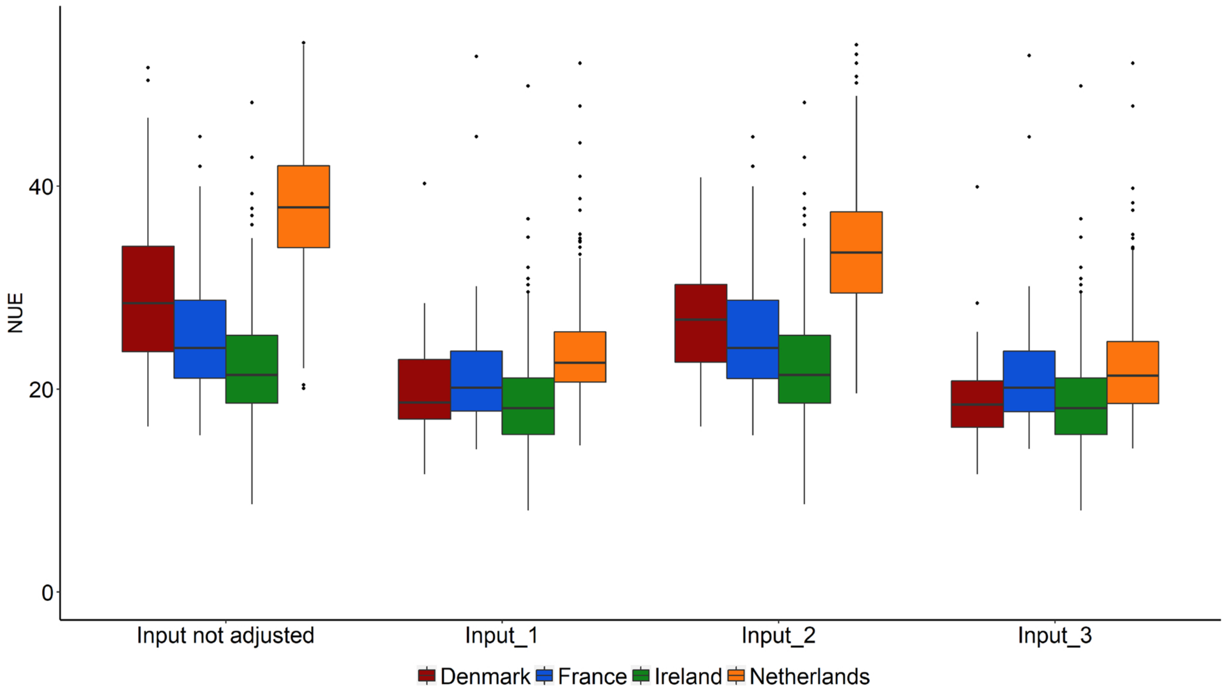

Fig. 8. Nitrogen use efficiency (NUE) for dairy farms comparing calculation of N input adjusted and non adjusted for N externalisation. Adjusted N input was calculated by either multiplying the net N imported as feed by 2 (Input_1, corresponding to a feed production NUE of 50%), by not considering manure N output as a negative input (Input_2, assuming a zero N fertiliser value for the manure), and as a combination of both adjustments (Input_3). Boxes and whiskers show 5 and 95% percentiles, boxes 25% (Q1) and 75% (Q3) quartiles and the line in the middle the median; single dots indicate outlying values.

Mean NUE was higher in Denmark than in France, in part because Danish farms had a higher level of externalisation through manure export and feed import (Fig. 6A, C).

Adjusting N inputs for externalisation had significant effects on NUE and N surplus of animal farms (Table 2), particularly on the NUE of dairy farms from the Netherlands (Fig. 8). Especially assuming a NUE of 50% for imported feed production (by multiplying the net N imported feed N by 2) decreased the farm NUE for all, but in particular for the Danish and Dutch farms, which had higher feed net import (Fig. 6). Not considering manure N export decreased mean NUE of dairy farms to a lesser extent than for adjusting feed import in all countries except Ireland given that this is not a common practice. Combining both adjusting factors (for feed import and manure export; N inputs_3) tended to equalise mean farm NUE for all countries, but significant differences between countries remained ($p < 0.001$). The pairwise comparison of means distinguished two different NUE groups, one involved The Netherlands and France (mean NUE, 22%) and the other Ireland and Denmark (mean NUE, 19%). The mean N input and N surplus increased in all countries (Supplementary S1 and S2).

After adjusting farm N indicators for externalisation, the Q1 and Q3 NUE values for dairy farms were 17 and 22% and the median N surplus increased to 255 kg N ha^{-1} (Fig. 5B). The median N input was 378 kg N ha^{-1} with 50% of the farms having inputs between 230 and 459 kg N ha^{-1}. In accordance, the modest target NUE for dairy farms after adjusting for externalisation was 20%, and the ambitious target 22%. The modest target N surplus increased up to 255 and the ambitious target to 180 kg N ha^{-1}.

The sensitivity analysis showed that the adjusting factor for net N imported as feed had a major impact on NUE in all countries and highlighted the need to define adjusting factors depending on feed nature and origin (Fig. 9). If feed is imported from farms with low NUE, a relatively large adjusting factor should be used to adjust for the externalisation of feed production. Additionally, if long-distance transport is required to bring feed to the farm gate, N losses associated with transportation should be incorporated into the adjusting factor as well. If the imported feed is locally produced from crop residues and by-products of the food industry, the adjusting factor may be low. These results are in agreement with de Klein et al. (2017), who proposed considering the N required to produce the imported feed, instead of the actual N imported in the feed, when calculating N inputs for a dairy farm.

The adjustment for manure export had a smaller effect on NUE than the adjustment for feed import (Supplementary S3). Manure export had an effect on the NUE of Dutch and Danish dairy farms and little or no effect on the NUE of French and Irish farms, because their manure export was minor or nil. However, the importance of adjusting N inputs for manure export on NUE and N surpluses will be larger for specialised, landless animal farms. The externalisation effect greatly depends on the fertiliser N effectiveness value of the exported animal manure, which varies greatly in practice (Steinfeld et al., 2006; Gourley et al., 2012; Webb and Erasmus, 2013); therefore, our hypothesis of 0% use is probably not always the most relevant.

The feed N import on dairy farms was clearly related to animal density (Supplementary S4). When increasing the number of livestock units per ha, farms become more dependent on imported feed. Feedlots with high animal density may be efficient due to the externalisation of feed production and manure export (Gourley et al., 2012; de Klein et al., 2017). Hence, adjusting for externalisation is especially important for livestock farms with high livestock density, including feedlots. However, a large scatter is observed in the relationship between livestock density and feed import (Supplementary S4), which may be related to differences in crop productivity (forage yield), cow productivity (feed requirements) and management practices regarding N losses.

The relationship between NUE and N input revealed a large scatter with a tendency toward higher N inputs and higher NUE with increasing animal density (Fig. 10A). After adjusting for externalisation, using Ninputs_3, the relationship between NUE and N inputs showed a completely different picture, due to a strong NUE decrease of farms with high livestock density (Fig. 10B). It also seemed to draw an efficiency frontier shaped as a decreasing exponential curve. Only certain farms with low to medium livestock density (1–3 LU/ha) had NUE

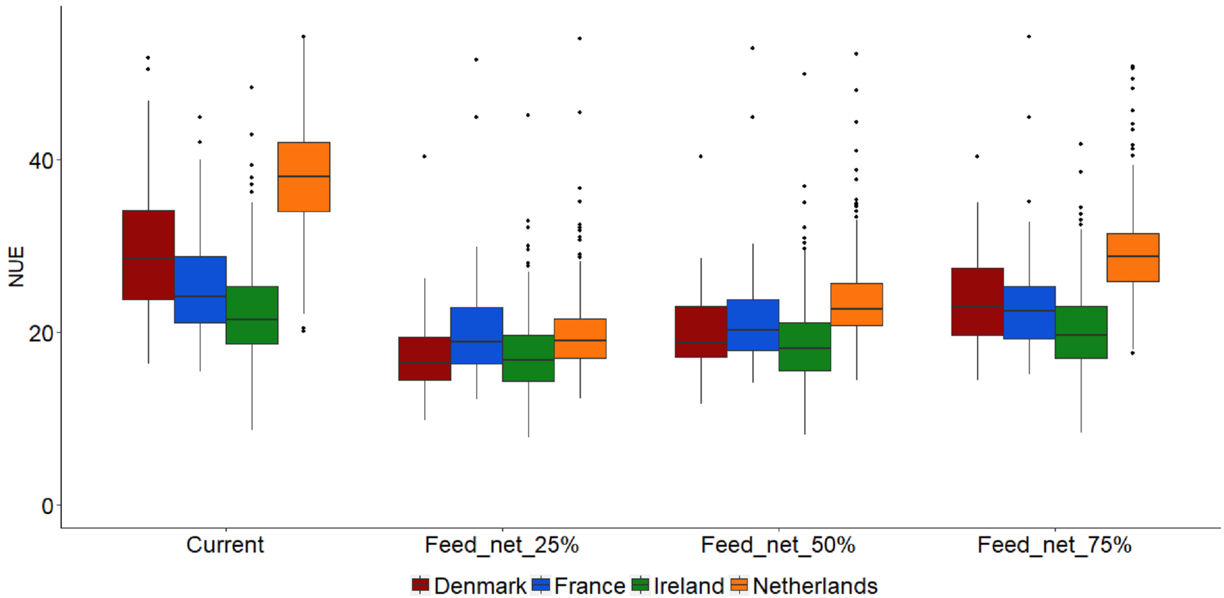

Fig. 9. Sensitivity analysis of nitrogen use efficiency (NUE) to net N imported as feed. Current calculations compared to calculate the N input assuming a NUE of 25%, 50% or 75% of the feed produced outside the farm. Boxes and whiskers show 5 and 95% percentiles, boxes 25% (Q1) and 75% (Q3) quartiles and the line in the middle the median; single dots indicate outlying values.

higher than 40%, while almost all farms with livestock density above 3 LU/ha had NUE below 30%. A possible explanation for this is that farms that produced their forage and feed had higher crop NUE than the 50% used for purchased feed, which became dominant in farms with higher N inputs. It is also remarkable that very extensive systems with LU $<$ 1 seemed less efficient than slightly more intensive systems. It is in the medium-low density systems where we found high diversity and the widest range of NUE. Therefore, there is a high potential for improvements that warrants further investigation in the future.

To overcome limitations of NUE value interpretation related to externalisation of N inputs and changes in soil N stock, Godinot et al. (2014) proposed an alternative indicator to assess system nitrogen efficiency (SyNE) at a farm level. Differences between SyNE relative to farm NUE are mainly related to the estimation of N emissions beyond the farm using a life cycle inventory approach and considering soil N stock variations. As a consequence, SyNE values are lower than NUE, particularly for animal farms (Godinot et al., 2015). Other attempts to develop N use efficiency indicators are also based on life cycle analysis and include the full N cycle chain, from the crop to the consumer (Uwizeye et al., 2016). However, the calculation of these indicators at

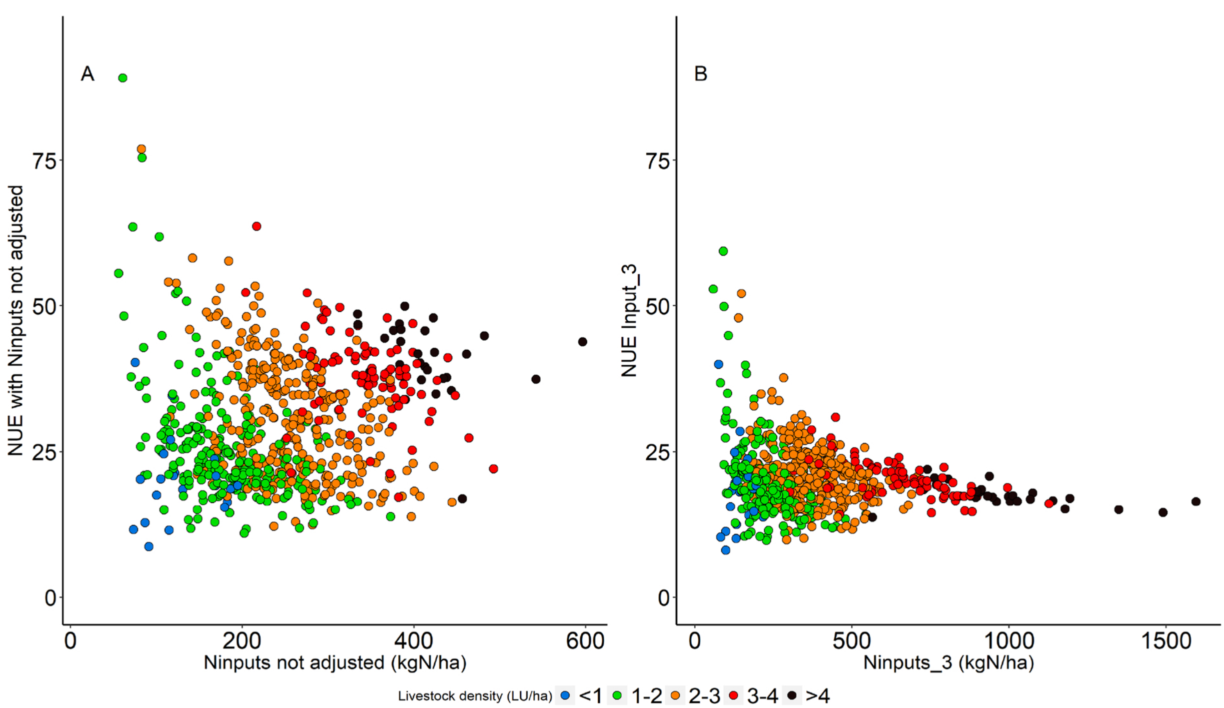

Fig. 10. Nitrogen use efficiency (NUE) versus N inputs comparing (A) calculation of N input with no adjustment with (B) calculating N inputs by multiplying the net N imported as feed by 2 (corresponding to a 50% feed production NUE) and not considering manure N output as a negative input (assuming zero N fertiliser value for manure) (Input_3).

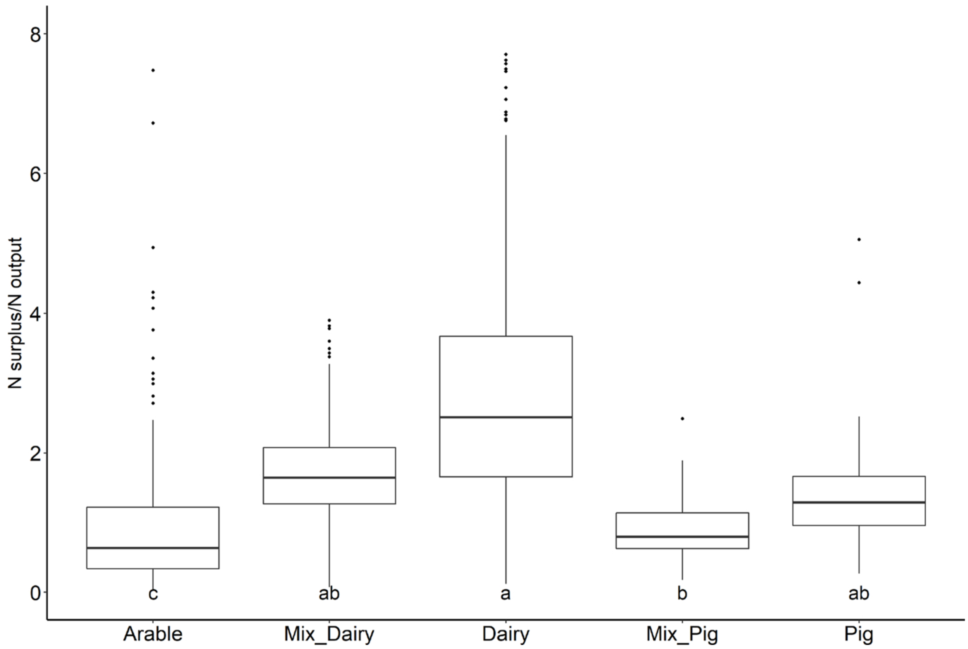

Fig. 11. Nitrogen emission intensity, calculated as the N surplus to the N output ratio, for the various farm types.

the farm level is complex, because obtaining high-quality and specific data for the LCA is a major effort that requires specific knowledge on where feed originates and how it was produced. Additionally, using the farm boundaries to define the system has the additional advantage that decision-taking by farmers has a direct effect on the outcome of the farm N indicators and that policy measures can be evaluated more easily at the farm level.

Other indicators combining production and environmental metrics have been proposed for characterizing farm performance, such as emission intensity (also called yield-scale emissions) or the N product per N emitted (Mosier et al., 2006; Van Groenigen et al., 2010). As an example, the emission intensity factor was calculated as the ratio between the N surplus and the N output for the various farm types and showed the lowest N emission per N exported for the arable farms and the highest for the dairy (Fig. 11). These indicators can reinforce the results from the analysis, and at the same time highlight the need for a systematic data collection that allows characterizing and comparing farm populations composed of a large number of observations. Our analysis could be applied to investigate alternative metrics for farm populations and even to develop specific indicators for the various farm types as it has been already proposed in limited datasets of dairy farms (Gorley et al., 2012; de Klein et al., 2017).

The data set for pig farms was much smaller than the dairy data set and only derived from one country (Denmark). For the pig farms in the data set, the Q1 and Q3 NUE values were 37 and 51%, respectively, which were higher than those for dairy, and the median N surplus (138 kg N ha^{-1}) was slightly lower than that from the dairy farm data set (Table 2), whereas the N output was higher (114 kg N ha^{-1}). This may be explained by the higher feed conversion efficiency of pigs compared to dairy cows (Godinot et al., 2015; Lassaletta et al., 2019) and the larger sale of crop products (Table 3). On average, N in animal products exported from the pig farms was 86% of total N exported, whereas in dairy farms it was 98% (Table 3). These results suggest that a possible modest NUE target for these pig farms is 37% and a more ambitious target 50%. A modest target N surplus would be 138 and the ambitious target N surplus 116 kg N ha^{-1}. These results have to be considered with caution, because they are derived from Danish pig farms with a significant fraction of crop products in the output and with a high proportion (44%) of organic farms. As in dairy farms, there is no indication of soil nutrient depletion (NUE approaching or exceeding 90%) and hence the data cannot be used to establish an upper NUE limit.

The Q1, median and Q3 farm N indicators for mixed livestock farms were between the values for corresponding specialised farms, whether dairy or pig or arable farms (Table 2). On average, the N in animal products exported from mixed dairy farms and from mixed pig farms was 54% of total N exports (Table 3).

As in dairy farms, accounting for externalisation of feed production and manure utilisation greatly reduced NUE and increased the N surplus values of pig farms, and to a lesser extent of mixed livestock farms (Table 2). These results reinforce the importance of accounting for externalisation.

3.4. Other factors and general discussion

Soil organic matter is an important store of N that is assumed to be stable in NUE calculations at the farm level. Annually about 2% of the organically bound soil N is mineralised and then becomes available to plants (Kirkby et al., 2011). This N is not free of charge, given that the soil organic N store is depleted. Hence, the soil organic N store should be replenished, through the supply of stubbles and roots, crop residues and green manures, animal manure and other organic or mineral fertilisers that enhance immobilisation in the soil microbial biomass. Soil organic C and N storage are stimulated when N inputs increase crop biomass and the return of crop residues into the soil, however, when N inputs are above the crop demand additional N inputs can increase residual inorganic N and enhance SOC mineralization reducing soil N storage (Poffenbarger et al., 2017). Changes in soil organic N and C are common following changes in, for example, crop rotation and especially following the conversion of permanent grassland to arable land and vice versa (Jarvis et al., 1996), and the conversion of rain-fed to irrigated land (Quemada and Gabriel, 2016). Changes are also common following manure applications, changes in soil cultivation practices, and changes in weather conditions (Maillard and Angers, 2014). These changes can have a substantial effect on NUE, N output and N surplus. However, measuring changes in soil organic N content is complex, because the spatial and depth variations in soil N content are high, and they are detectable in long-term monitoring only. Godinot et al. (2014) tried to overcome this limitation by modeling soil organic matter content in a limited set of farms and concluded that organic N changes had a large effect on farm N indicators. It is not an easy task to model how soil organic matter evolves for a large number of farms; we therefore recommend that reports on NUE at the farm level include a discussion about the possibilities and risks of changes in soil organic N with time. If a likelihood of soil accumulation or mining is observed, the NUE indicators suggested should be interpreted with caution, until a more detailed study can be conducted on changes in soil C and N stocks.

In irrigated cropping systems, N content in irrigation water varied from negligible to 159 kg N ha^{-1} depending on the amount and origin of irrigation water. Water coming from rivers and reservoirs had low N concentration, whereas high concentrations may be found when pumped from aquifers already polluted with nitrate or reused for irrigation water from food processing or water treatment plants. Many farmers tend to underestimate this source of N and even think about it as a positive extra supply. However, in many farms it becomes a relevant input that has to be accounted for in the N balance; otherwise it can increase N surplus greatly.

In the data set, biological N fixation varied from 0 to 154 kg N ha^{-1} and it is recognised as a relevant source of uncertainty, particularly in grasslands containing legumes such as clover (Nevens et al., 2005; Powell et al., 2010). The proportion of clover in grasslands was analysed for some farms, but not all of them. This uncertainty can have a substantial influence on NUE and surplus results (Godinot et al., 2014). However, we think that the tier methodology offers a good compromise, given that it allows users to estimate biological N fixation following defined rules, with more or less precision depending on the available data. We recommend that, when possible, the tier level approach on data collection should be reported to better asses data quality.

Crops not devoted to produce protein may have low N output and NUE (i.e. globally averaged NUE for fruits and vegetables of 14%; Zhang et al., 2015) but still be necessary for providing products demanded by the society. Therefore, specific N targets should be developed for cropping systems involving crops not devoted to produce protein and may be combined with other indicators related to the main product.

Finally, N indicators depend not only on farmers' production choices and practices, but also on the soil and climate. This dimension was not specifically studied in our data set, due to limited information on environmental conditions of the farms, but it is nonetheless integrated into the results. Limitations on the data collection may arise from data protection policies, particularly those concerning location that may allow farm identification, but a systematic collection of soil and climate data is recommended in the guidance document as it would allow further analysis connecting farm N indicators targets and environmental conditions. The aim of this study is not to define limits, ceilings and target values per farm type, but rather to provide a framework for analyses and discussion of NUE as a key sustainability indicator. Adapting target values to other contexts and systems requires an analysis similar to the one presented here, to account for differences in farm type, crops, regional environmental regulations, and diverse agro-climatic conditions.

4. Conclusions

A simple and robust monitoring protocol ensured consistency in N farm-gate balances and allowed comparison of performance among ~1240 farm observations from six countries examined across EU. Arable farms had the lowest mean N input and N surplus and the highest mean N output and NUE among the five farm types. In contrast, livestock farms had the highest mean N input and N surplus, and the lowest mean N output and NUE. Mixed crop/livestock farms had values between these two extremes. Median NUE was 61% for arable farms, 28% for dairy and 43% for pig farms. The farm data originated from different studies and even if were analyzed following a common protocol and procedure they are not necessarily representative of the farms in each country. Overall, the differences in NUE between farms were mainly related to differences in farm type (type of production), management (production intensity and practices) and probably also soil and climate conditions. Nitrogen outputs reflect differences in farm types and management as well as in regions and countries.

Including N losses external to the farm had a large effect on animal farm N indicators, and the results highlight the need for considering adjusting factors when calculating and interpreting the farm balance. The N input should account for the N required to produce the imported feed instead of the actual N imported in the feed, and for N losses associated with manure export or management. After accounting for external N losses in feed imports to and manure exports from the farm, median NUE decreased to 19% for dairy farms and 23% for pig farms.

Farm N indicators were useful to compare farm performance among different farming systems and countries and to define a COS for a farm population, even if caution should be taken when comparing livestock farms before externalisation adjustments are made. Farms outside their agro-environmental optimum should change production practices to approach their specific targets. Depending on their current situation, this can be done by increasing or reducing N inputs only (intensification or extensification pathways), or other strategies may also be necessary to increase agro-environmental performance (sustainable intensification pathways). The conceptual diagram proposed by the European N expert panel provides an excellent framework to analyse farm performance as well as options for farmers and policy makers.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agsy.2019.102689.

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